Turbulent Flow and Large Surface Wave Events in the Marine Boundary Layers

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LONG-TERM GOALS

The long term objective of our research for the "High Resolution Air-Sea Interaction" (HRES) Departmental Research Initiative (DRI) is to identify the couplings between large wave events, winds, and currents in the surface layer of the marine boundary layers. Turbulence resolving large eddy simulations (LESs) and direct numerical simulations (DNSs) of the marine atmospheric boundary layer (MABL) in the presence of time and space varying wave fields will be the main tools used to elucidate wind-wave-current interactions. A suite of turbulence simulations over realistic seas using idealized and observed pressure gradients will be carried out to compliment the field observations collected in moderate to high winds. The database of simulations will be used to generate statistical moments, interrogated for coherent structures, and ultimately used to compare with HRES observations.

OBJECTIVES

Our near term goals are: 1) participate in the planning process for the HRES field campaign; and 2) construct an LES code applicable to the HRES high wind regime. In order to accomplish the latter goal we are improving the parallelization of our base LES code and developing an algorithm to allow simulations of turbulent winds over nearly arbitrary 3-D wave fields.

APPROACH

We plan on investigating interactions between the MABL and the connecting air-sea interface using both LES and DNS. The waves will be externally imposed: (1) based on well established empirical wave spectra; or (2) ultimately provided by direct observations of the sea surface from field campaigns. The main technical advance is the development of a computational tool that allows for nearly arbitrary 3-D wave fields, *i.e.,* the sea surface elevation $h = h(x, y, t)$ as a surface boundary condition. The computational method will allow time and space varying surface conditions over a range of wave scales $\mathcal{O}(10)$m or larger.

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WORK COMPLETED

Meetings: We attended a PI meeting in Monterey CA that focused on refining elements of the HRES field campaign. The discussion concentrated on the atmospheric measurements to be collected from aircraft and from R/V FLIP with particular attention paid to the surface layer pressure measurements. A summary of the discussion is available from C. Friehe (U.C. Irvine). We also presented a summary of our modeling results from the HRES and ITOP (Impacts of Typhoons on the Western Pacific Ocean) departmental research initiatives at the ONR program review (June, 2009) in Chicago.

Publication: Last year we wrote an article for *Annual Review of Fluid Mechanics* (see Sullivan & McWilliams, 2010). Our contribution discusses the coupling processes between surface gravity waves and adjacent winds and currents in the marine boundary layers. Wind-wave and wave-current interactions are important as these processes modulate the exchanges of momentum, heat, and gases between the atmosphere and ocean. Atmospheric processes we discuss are wind-driven waves, wave-driven winds, steep waves and drag laws. In the ocean boundary layer, we summarize the currently accepted views of wave-current interactions, the modeling of Langmuir circulations, impacts of breaking waves, and the implications of wave-current interactions for mixing at high winds.

Algorithmic Developments: During the past year we began adapting our parallel LES code (Sullivan & Patton, 2008) to accommodate a general 3D time varying wavy surface. This was accomplished in the following stages: a) Develop the governing equations for an atmospheric PBL in curvilinear time-dependent surface-following coordinates; b) Build and test a module capable of generating a 3D wavy surface; and c) Implement and test a) and b) in our "flat bottom" parallel LES code for the atmospheric PBL.

Introducing a 3D moving bottom boundary adds significant complexity compared to our previous boundary-layer simulations with a single monochromatic wave (Sullivan *et al.* 2007). Here, we briefly outline a few key elements of the problem formulation and computational implementation for the general wavy bottom problem with emphasis on the treatment of advection and pressure [further details are available in Sullivan (2010)]. In the present formulation the advection of momentum and scalars, and also subgrid-scale energy in the case of LES, $(\rho u_i, \theta, e)$ is written in flux conservative form using a contravariant velocity that takes into account grid movement. A generic transport equation for variable ψ in time-dependent surface following coordinates takes the form

$$\frac{\partial}{\partial t}\left(\frac{\psi}{J}\right) \; + \; \frac{\partial}{\partial \xi_j}\left[\psi(U_j - z_t\delta_{3j})\right] \; = \; \frac{\mathcal{R}}{J} \tag{1}$$

where $\boldsymbol{\xi} \equiv \xi_i \equiv (\xi, \eta, \zeta)$ are computational coordinates, U_j is the contravariant flux velocity, z_t is the grid speed (*i.e.,* the speed at which vertical grid lines translate), J is the Jacobian connecting physical and computational spaces $\mathbf{x} \Rightarrow \boldsymbol{\xi}$, and the right hand side $\mathcal{R}$ includes the appropriate combination of pressure, buoyancy, viscous, Coriolis, and diffusion terms. Since the grid is constrained to translate vertically the grid motion only contributes vertical flux ψz_t. Also, included in our equation set is the geometric or space conservation law (SCL) (Thomas & Lombard, 1979) which relates the change of an elementary control volume to the co-ordinate frame velocity. Inspection of the advective term in (1)[1] shows that with constant ψ and uniform velocity the SCL is

[1] The space conservation law follows most naturally from the continuity equation written for a variable density fluid.

$$\frac{\partial}{\partial t}\left(\frac{1}{J}\right) = \frac{\partial}{\partial \zeta}\left(\frac{\partial z}{\partial t}\right). \tag{2}$$

With an externally imposed surface wavefield, either J or z_t can be specified at future time steps. Then the SCL is satisfied by computing the counterpart z_t or J according to the particular discretization of (2). In our implementation, we choose to compute z_t based on knowledge of J at forward time steps.

Our boundary-layer model, using DNS or LES, adopts the incompressible Boussinesq assumption and thus an elliptic Poisson equation for a pressure variable p must be solved in order to satisfy the continuity equation. This is the major computational issue in modeling incompressible flows above terrain. The pressure Poisson equation for a surface following grid, developed from the continuity equation expressed in terms of contravariant flux velocities, $\partial U_i/\partial \xi_i = 0$, is

$$\begin{aligned}&\frac{\partial}{\partial \xi}\left(\frac{1}{J}\frac{\partial p}{\partial \xi}\right) + \frac{\partial}{\partial \eta}\left(\frac{1}{J}\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \zeta}\left(\frac{\zeta_x^2+\zeta_y^2+\zeta_z^2}{J}\frac{\partial p}{\partial \zeta}\right) + \\ &\frac{\partial}{\partial \xi}\left(\frac{\zeta_x}{J}\frac{\partial p}{\partial \zeta}\right) + \frac{\partial}{\partial \eta}\left(\frac{\zeta_y}{J}\frac{\partial p}{\partial \zeta}\right) + \frac{\partial}{\partial \zeta}\left(\frac{\zeta_x}{J}\frac{\partial p}{\partial \xi} + \frac{\zeta_y}{J}\frac{\partial p}{\partial \eta}\right) = \mathcal{S}.\end{aligned} \tag{3}$$

where $\mathcal{S}$ is the divergence of the right hand side of the momentum equations and $(\zeta_x, \zeta_y, \zeta_z)$ are metrics arising from the coordinate transformation. Direct solution of this elliptic equation is not readily possible using the standard method of 2D Fourier transformation in horizontal planes followed by a tridiagonal matrix solve for each pair of horizontal wavenumbers (k_x, k_y) (*e.g.,* Sullivan *et al.* 2000). This is due to the variable coefficients and mixed derivatives resulting from the grid transformation. Instead, we enforce mass conservation by iteratively solving

$$\nabla^2_D\, p^{(n+1)} = \nabla^2_D\, p^{(n)} + \frac{1}{\Delta t \gamma}\boldsymbol{\nabla}\cdot\mathbf{U}^{(n)}, \tag{4}$$

for the pressure p. In (4), n is the iteration index, Δt is the time step and γ is a weight associated with the time integration. $\nabla^2_D\, p$ is a diagonal pre-conditioning matrix that can be inverted using standard methods. Tests indicate that this iterative scheme is robust and converges the solution for p to machinery accuracy with roughly $n = 30$ iterations for waves of modest slope $ak \sim 0.1$. More demanding tests with steep waves (and hills) are planned.

A wavy-bottom DNS/LES boundary-layer model is completed by specifying the wavefield $h = h(x, y, t)$ and appropriate boundary conditions. As a first step, we build $h(x, y, t)$ from a linear combination of simple plane waves. The amplitudes and phases of the components are picked to mimic properties of the wave field, *e.g.,* short or long crested waves, wave propagation direction, or measured wave height spectra (*e.g.,* Pierson and Moskowitz, 1964). This flexibility allows us to conduct idealized process studies with a known wavy surface but also provides the framework to ingest measured wavefields from the HRES field campaign. Periodic boundary conditions are used in the horizontal (ξ, η) directions as is customary for boundary layer simulations. At the air-water interface, the atmospheric motions are set equal to the the water orbital velocities. At the present time, the wave motions are assumed to be irrotational.

The numerical method used to solve the transport equations for momentum, scalars and subgrid-scale energy, the pressure Poisson equation, and the space conservation law are broadly similar to those described in Sullivan *et al.*(2000, 2007). The spatial differencing is pseudospectral along computational coordinate lines (ξ, η) and second-order finite difference along the vertical coordinate line ζ. A third-order Runge-Kutta time stepping scheme operating with a fixed CFL number is used to advance the equations in time. We emphasize that identical numerics are used to solve the momentum and space conservation laws in order to avoid false generation of sources and sinks due to the grid movement (*e.g.,* Ferziger and Perić, 2002). A fractional step projection method is used to enforce mass conservation on the contravariant flux velocities. The most expensive step of the solution procedure is the iterative solution of the pressure Poisson equation (4).

The parallel implementation of the wavy-bottom algorithm outlined above utilizes a 2D domain decomposition similar to our "flat bottom" turbulence simulation code. Each processor operates on three-dimensional "bricks" sub-sampled in x, y, or z directions. Brick-to-brick communication is a combination of transposes and ghost point exchange. To preserve pseudospectral differencing in the horizontal directions a custom parallel matrix transpose was designed and implemented. Finally, a new pressure Poisson solver was coded to match the domain decomposition [further details are given in Sullivan & Patton, (2008), Sullivan (2010)].

RESULTS

The computational algorithm and component parts described in the WORK COMPLETED section are currently being implemented and evaluated for idealized cases. Figures 1 and 2 are typical snapshots of instantaneous wavefields generated by our virtual wave algorithm. In each figure, the wave amplitudes are chosen to match the Pierson-Moskowitz wind-wave equilibrium spectrum for winds of 15 ms^{-1}. In figure 1 the waves propagate with no directional dependence while in figure 2 long crested waves propagate across the grid. In these examples, the space and time scales of the wavefields lie in the resolved scale regime of an atmospheric LES. Figures 3 and 4 are illustrative examples of LES of atmospheric boundary layers with complex surface layers. In figure (3), we show the near surface boundary-layer wind field around an isolated 3D hill of height 50 m. The winds are driven by a mixture of surface heating $Q_* = 0.05$ K ms^{-1} and geostrophic winds $(U_g, V_g) = (5, 0)$ ms^{-1}. The boundary-layer depth is $\mathcal{O}(1000)$ m. Notice the speedup of the winds near the crest and sides of the hill. In figure (4) we show contours of the horizontal wind at a height of 6 m above a two-component propagating surface wave field. These trial simulations demonstrate that the new LES code is functional and capable of handling complex lower boundaries. In the future we plan a detailed validation of the wavy bottom simulation code using the rough-hill wind tunnel measurements described by Gong *et al.* (1996) and the wind-wave tank observations described by Veron *et al.* (2007). These are demanding test cases as they include regions of extensive flow separation.

IMPACT/APPLICATIONS

The computational tools developed and the database of numerical solutions generated will aide in the interpretation of the observations gathered during the HRES field campaigns. In addition idealized process studies performed with the simulations have the potential to improve parameterizations of surface drag under high wind conditions in large scale models.

TRANSITIONS & RELATED PROJECTS

We are currently engaged in analyzing data collected during the Ocean Horizontal Array Turbulence Study (OHATS) and the Coupled Boundary Layers Air-Sea Transfer (CBLAST) field campaigns. These are joint efforts between NCAR, and numerous university investigators. Also the present work has links to the ONR DRI on the impact of typhoons in the Western Pacific Ocean (ITOP).

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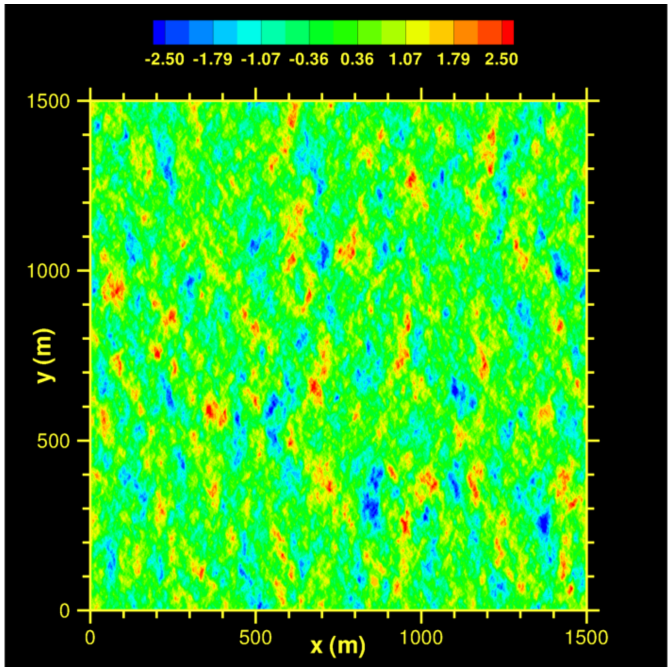

Figure 1: An example of a virtual wave field generated by linear combinations of plane waves. The amplitudes of the individual components are picked to match a Pierson-Moskowitz wind-wave equilibrium spectrum at a wind speed of 15 m s^{-1}. The wavefield is sampled at a resolution of $\Delta x = \Delta y = 2.9$ m and propagates from left to right. The wave height amplitude $h = h(x, y, t)$ shown in the color bar is in units of meters.

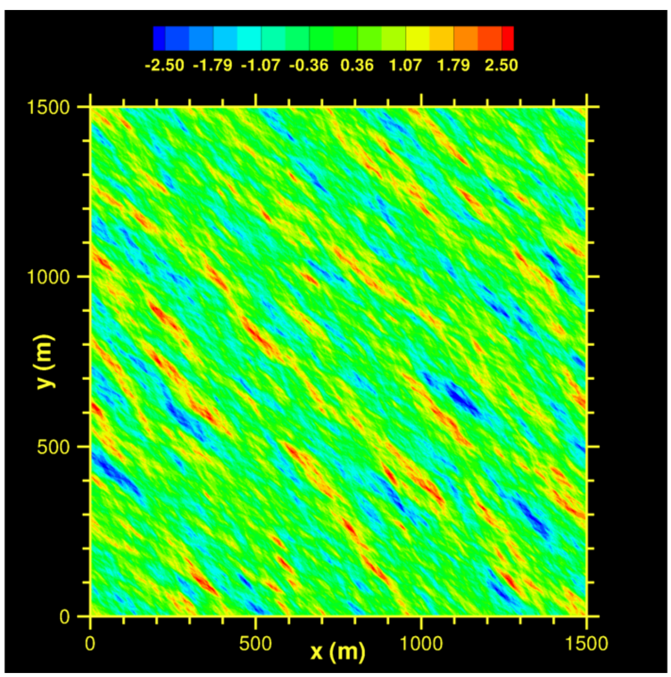

Figure 2: An example of a wave field propagating across the $x - y$ computational grid with a directional distribution function chosen to emphasize long crested waves. The wind speed and grid resolution are identical to those in figure 1.

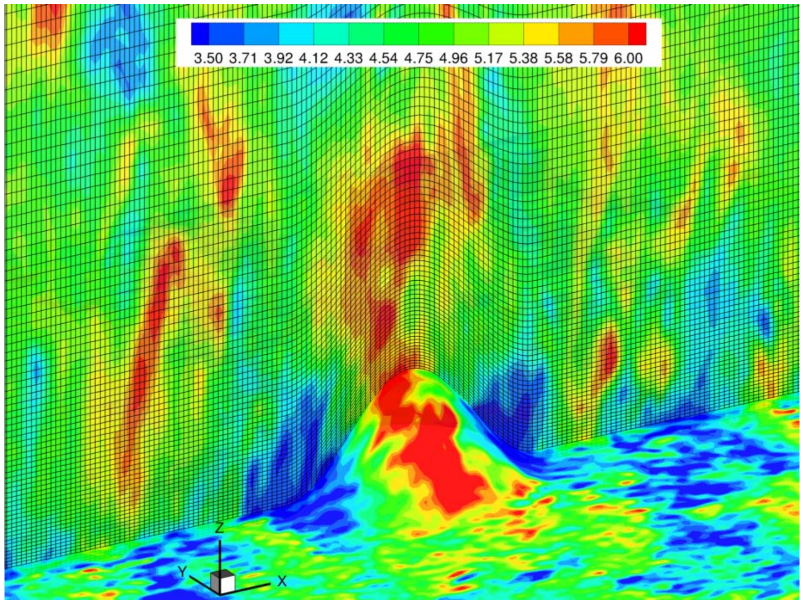

Figure 3: The turbulent wind field ($u-$ component) around and above an isolated hill in a mixed convective-shear driven atmospheric boundary layer - surface heat flux $Q_* = 0.05$ K m s^{-1} and geostrophic wind $U_g = 5$ m s^{-1}. The 3D cosine shaped hill is 50 m tall. Notice the wind speedup over the crest and side of the hill with $u/U_g > 1.2$. The color bar at the top of the figure is in units of m s^{-1}. This simulation employs $256 \times 256 \times 128$ gridpoints and demonstrates that the LES algorithm is capable of simulating turbulent flow above general topography.

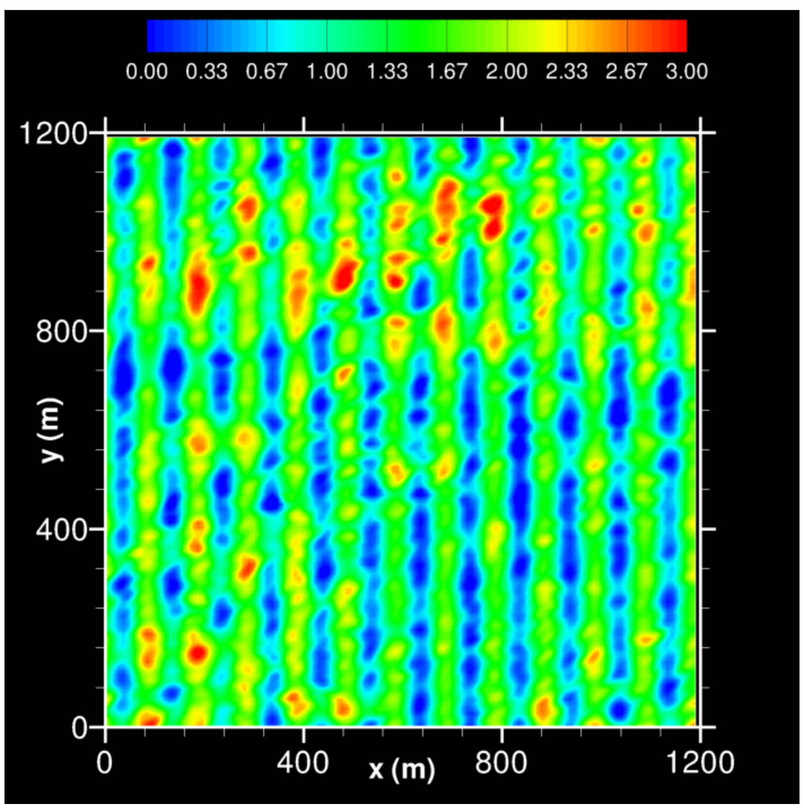

Figure 4: The horizontal $u-$component of the wind field at a height of 6 m above a moving two component wave field produced by large-eddy simulation. Pockets of high and low winds are concentrated around the crests and troughs of the wavefield. The color bar at the top of the figure is in units of m s^{-1}. The simulation employs $256 \times 256 \times 128$ gridpoints.